NUMERICAL EXPERIMENTS ON THERMAL CONVECTION IN A CHEMICALLY STRATIFIED VISCOUS FLUID HEATED FROM BELOW: IMPLICATIONS FOR A MODEL OF LUNAR EVOLUTION. K. M. Alley, E. M. Parmentier, and P. C. Hess, Department of Geological Sciences, Brown University, Providence RI, 02912

A model for the internal evolution the Moon explaining the origin of mare volcanism calls for the creation of a lunar core from the dense, ilmenite and incompatible element-rich cumulate crystallized during the final stage of a magma ocean. Radioactivity in this core heats the overlying chemically stratified mantle producing a hot, convecting, chemically well-mixed layer that increases in thickness with time. As it warms and thickens, the top of this layer eventually reaches the solidus temperature of overlying mantle resulting in melting that produces mare basalts more than 500 Myr after the crystallization of the magma ocean and formation of the lunar crust [1]. The stable chemical stratification traps, within the mixed layer, heat coming from the core. In the absence of this stratification, plumes would form rapidly (on the time scale to form an unstable thermal boundary layer), rise and melt near the top of the mantle failing to explain either the high pressure melting inferred for mare basalts or the age of their emplacement on the surface.

We have carried out numerical experiments that examine the formation of a heated mixed layer in an initially chemically stratified, viscous fluid heat from below [2]. The numerical experiments examine a simpler parameterized analysis on which our first assessment of the above lunar evolution model was based [1]. The numerical formulation of the model as well as results depicting the formation and evolution of a mixed layer have been previously described [2]. Here we report further analysis of the numerical experiments and their application to lunar evolution.

Two dimensionless parameters, a thermal Rayleigh number (R_T) and the ratio of compositonal to thermal buoyancy ($R \propto$ compositional density gradient/heatflux), that characterize each numerical experiment are defined in terms of the layer thickness, d, the initial stable compositional density gradient, and the prescribed, constant rate of heating from below, q. Mixed layer thickness as a function of time from numerical experiments for a range of R values with $R_T=3x10^7$ are shown in Figure 1. Smaller R, corresponding to a weaker chemical stratification, results in a more rapidly thickening mixed layer. Solid lines show the predicted thickening rate of the mixed layer based on the simple idealization shown in Figure 2. Two basic assumption of this idealized model are that the mixed layer is both thermally and chemically well mixed and that the density at the top of the mixed layer is equal to that at the bottom of the overlying fluid. If the latter were not true less dense fluid in the mixed layer would rise into the overlying fluid. Alternatively denser fluid in the mixed layer must warm up further before entraining overlying mantle thus allowing the mixed layer to continue thickening. This model predicts a mixed layer thickness $z^*=(2\kappa t/R)^{1/2}$ that agrees well with numerical experiments. Note that z* is independent of R_T (if the thermal Rayleigh number based on the mixed layer thickness is sufficiently large), a prediction generally confirmed by numerical experiments like those shown in Figure 1 for a range of R_T values. In contrast to this simple model, the numerical experiments show that a second mixed layer forms above the first for sufficiently high values of R. A conductive thermal boundary layer that develops in the stratified fluid above the top of the mixed layer becomes unstable resulting in the formation of the second layer. The development of a multiple layers would have important consequences for lunar evolution but appears to occur only for large values of R, i.e. a larger compositional gradient and/or a smaller heatflux than would be needed to explain lunar thermal evolution.

Horizontally-averaged temperatures as a function of height above the heated bottom of the fluid shown in Figure 3 would correspond to temperatures in the mantle above the ilmenite cumulate core. The heatflux and compositional density gradients are reasonable for the range of lunar models discussed earlier [1]. The dashed line shows an estimate of the solidus temperature of the lunar mantle. Depending on the values of theses two parameters, deep global melting at the top of the mixed layer would begin after 400-600 Myr as required to explain the origin of mare basalts.

References: [1] P. C. Hess and E. M. Parmentier, *Earth Planet. Sci. Lett. 134*, 501-514, 1995. [2] K. M. Alley and E. M. Parmentier, *LPSC 27*, 21-22, 1995.

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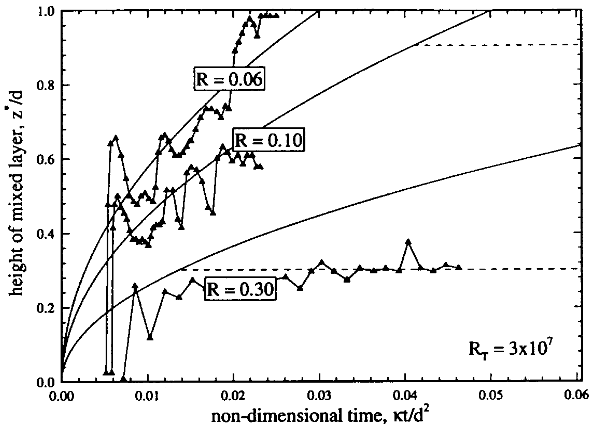

Figure 1. Mixed layer thickness as a function of time for a range of R values for a numerical experiment with R_T=3x10^7. The mixed layer thickens more slowly in the presence of an increasingly strong stable chemical stratification (increasing R). Results of two-dimensional numerical experiments (symbols) and the theoretical idealization described in Figure 2 (solid lines) agree well before a second layer forms. For sufficiently large R, the first mixed layer stops thickening as a second mixed layer forms above the first (horizontal dashed line).

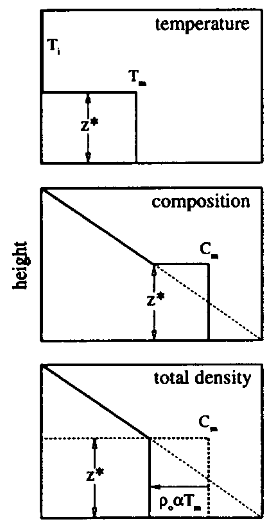

Figure 2. Idealization of horizontally averaged temperature (top), composition (middle), and the resulting total density (bottom). As shown by the solid lines in Figure 1, evolution of the mixed layer thickness is well described by requiring that the density at the top of the mixed layer equal that in the remaining, overlying stratified fluid.

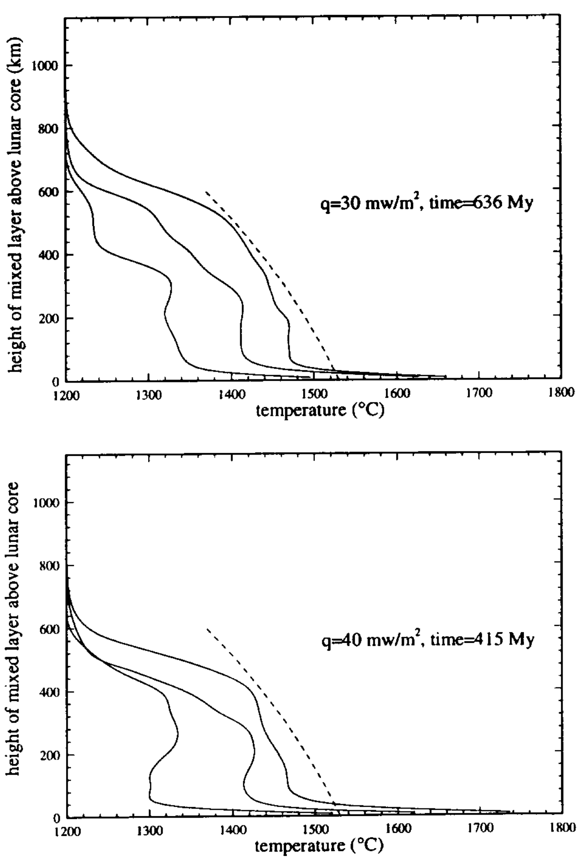

Figure 3. Horizontally averaged temperature at three equally spaced time intervals (solid lines) and melting temperature (dashed line) as a function of height above the hypothesized lunar core-mantle boundary. Result are shown for R=0.06 and two values of heatflux into the base of the mantle from the core. For heatfluxes of 30 and 40 mW/m^2, melting at the top of the mixed layer would commence at about 415 and 636 Myr, respectively.